# WHAT REGULATES SUSPENDED-SEDIMENT TRANSPORT IN A GIVEN SETTING? GRAIN SIZE OF BED SEDIMENT OR FLOW?

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## INTRODUCTION

**Background and purpose** It might be argued that the key question to ask when beginning an investigation of a natural sediment-transporting flow is whether transport is limited mainly by flow strength or sediment supply. The answer to this question determines whether research should focus on the relation between flow strength and sediment transport, the rate at which sediment of different grain sizes is supplied to the flow, or both. For a given setting, this is the key question that must be answered prior to either designing a sediment-transport measurement program or constructing a sediment-transport model or budget. This is also the key question to answer when calculating total maximum daily loads (TMDLs) for sediment.

Rubin and Topping (in press) developed a technique to evaluate the importance of changes in flow strength relative to changes in sediment supply in regulating the rate of sediment transport. If that technique determines that changes in suspended-sediment transport in a river (or on a continental shelf) are regulated mainly by flow, then a measure of the flow strength (e.g., the boundary shear stress, shear velocity, or discharge of water) may be an adequate predictor of sediment transport. In contrast, if changes in sediment transport are regulated mainly by changes in bed-sediment grain size, then measurements of sediment input will be a more accurate predictor of sediment transport than any measure of flow strength.

### Definitions

**Flow-regulated transport and bed-sediment-regulated transport** In a system where flow-induced changes in transport are large relative to bed-sediment grain-size-induced changes in transport, transport is defined to be flow-regulated. At the other extreme, where changes in bed-sediment grain size are the dominant factor regulating sediment transport, transport is defined to be grain-size-regulated.

**Suspended sediment, suspended bed material, and wash load** Suspended sediment includes two kinds of load: suspended bed material and wash load. In this paper, the term suspended sediment is applied to suspended bed material (thus excluding wash load). Suspended bed material includes those grain sizes that occur in substantial amounts in the bed, whereas wash load is finer than the bed sediment (Einstein and Chien, 1953). Another approach—compatible with (Einstein and Chien, 1953)—might be to base definitions on the concentration gradient; wash load would include those sizes having a concentration that remains constant with height above the bed.

## APPROACH

**Flow-regulated transport** Laboratory flumes that recirculate both sediment and water are ideal for studying flow-regulated transport, because grain size on the bed ($D_b$) remains nearly constant. Under such conditions, increases in shear velocity ($u_*$) from one experiment to another cause increases in concentration ($C$), grain size of suspended sediment ($D_s$), and sediment transport ($q$). $D_s$ and $C$ increase because stronger flows are able to suspend coarser sediment and more sediment, and $q$ increases for two reasons: concentrations are higher and more water is discharged. Because $C$ and $D_s$ increase with shear velocity, they are positively correlated (Fig. 1a).

**Bed-sediment grain-size-regulated transport** Grain-size-regulated transport can be studied by comparing data collected with differing bed-sediment grain sizes for a narrow range of $u_*$. Under such conditions, coarsening of the bed sediment causes concentration to decrease, while causing the median diameter of the suspended sediment to increase. As a result of these opposite responses to changes in $D_b$, $C$ is inversely related to $D_s$ where transport is grain-size regulated (Fig. 1b).

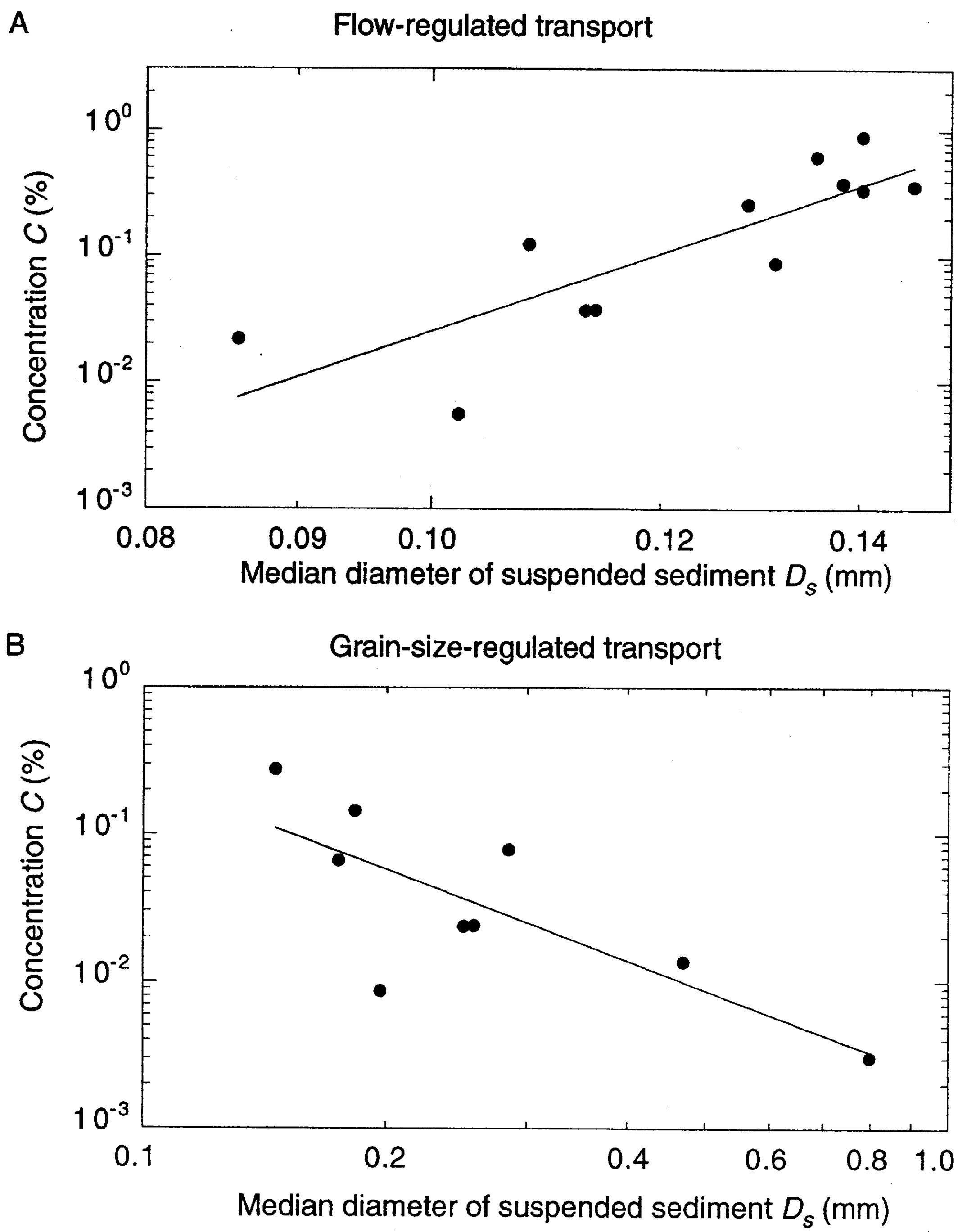


**Figure 1.** Relations between concentration and grain size for flow-regulated transport (A) and grain-size-regulated transport (B). **A.** Flow-regulated transport. Data are from laboratory experiments of Guy et al. (1966, Table 9); for all runs depth was 15-16 cm; sand in flume had a median diameter of 0.33 mm and sigma phi of 1.04. Concentration is weight percent of suspended sediment. $C$ and $D_s$ are positively correlated, because both increase with $u_*$. **B.** Grain-size-regulated transport in flume experiments. Plotted points represent all runs with $u_*$ between 7.0 and 8.0 cm/s in data of Guy et al. (1966, Tables 2-8). Increasing the grain size of sediment on the bed caused the concentration of suspended sand to decrease and the median diameter of suspended sediment to increase.

**Quantifying the relative importance of grain-size regulation and flow regulation of suspended-sediment transport** If transport in all flows were regulated purely by changes in flow or by changes in bed sediment, then the sign of $\Delta C/\Delta D_s$ would be a definitive distinguishing characteristic (positive for flow-regulated transport and negative for grain-size-regulated transport). Because all intermediate conditions are possible, however, definitive evaluation is more complicated. Rubin and Topping (in press) followed the approach discussed below.

Most models of suspended-sediment transport express transport as a function of some combination of flow properties (such as $u_*$, water slope, and water depth) and bed-sediment grain-size properties (such as median diameter $D_b$ and standard deviation). The simplest approach to quantifying the relative importance of a single change in both flow and a change in bed-sediment texture is to evaluate their individual impacts on the transport rate. For such a change, this measure $\alpha$ can be defined as

$$\alpha = \frac{\log\left[q(flow_1, grain-size_1)/q(flow_1, grain-size_2)\right]}{\log\left[q(flow_1, grain-size_1)/q(flow_2, grain-size_1)\right]} \qquad (1)$$

where $q$ gives the sediment-transport rate as a function of both flow and bed-sediment grain size; subscripts refer to conditions at two times. The numerator quantifies the extent to which a change in transport rate is influenced by the change in bed-sediment grain size (holding flow constant), while the denominator quantifies the effect of the change in flow alone. $\alpha$ is a dimensionless number that describes how much of a change in transport is caused by a change in bed sediment relative to a change in flow. Where sediment transport is regulated primarily by changes in bed-sediment grain size, $|\alpha| >> 1$; where transport is regulated primarily _by changes in flow, $|\alpha| << 1$; and where transport is regulated equally by changes in flow and bed sediment, $|\alpha| = 1$.

To evaluate the functional relations expressed in eq (1), Rubin and Topping (in press) used the following approach:
(1) A numerical model based on McLean (1992) was used to calculate concentration of suspended sediment at 500 logarithmically spaced elevations above the bed, for 129 size classes of bed sediment binned in 1/16 $\phi$ increments. The algorithm was used to predict mean concentration and median grain diameter for more than 1000 combinations of flow variables, including 11 median grain diameters (0.03 to 1.2 mm), 20 values of $u_*$ (from below threshold of transport to upper plane-bed regime), 3 depths (10, 100, and 1000 cm), and both narrow and wide log-normal bed-sediment grain-size distributions. The computations were repeated for a more complex algorithm that included development of dunes.
(2) Concentration and grain size of suspended sediment were averaged through the water column.
(3) The computed results were then approximated by equations expressing the dependent variables ($C$ and $Ds$) as power functions of the independent variables ($u_*$ and $D_b$).
(4) The equations derived in step (3) were rearranged, so that the independent variables $u_*$ and $D_b$ were expressed in terms of the more easily observed dependent variables $C$ and $D_s$. This sequence of steps led to

$$\alpha = \left(\frac{K}{J+1}\right)\frac{-L\left(\frac{\log\Delta C}{\log\Delta D_s}\right)+J}{M\left(\frac{\log\Delta C}{\log\Delta D_s}\right)-K} \qquad (2)$$

where the values of $J$ and $K$ for various models listed in step (1) are given in Table 1.

**Table. 1** Values of J, K, L, and M in equations (2 and 5), determined by fitting power laws to computational results.

| Model | J | K | L | M |
|---|---|---|---|---|
| Without dunes; sigma phi=0.55 | 3.5 | -2.5 | 0.15 | 1.0 |
| Without dunes; sigma phi=1.4 | 3.5 | -1.5 | 0.4 | 0.5 |
| With dunes; sigma phi=0.55 | 5.0 | -3.0 | 0.2 | 0.7 |
| With dunes; sigma phi=1.4 | 3.5 | -1.5 | 0.3 | 0.5 |

The symbol ? in eq (2) applies to a single change in conditions; for results to be representative of a more extensive set of time-series measurements, it is necessary to replace the ? with a statistical measure. The approach taken here is to replace ? with the standard deviation of a variable, so that $\log\Delta C/\log\Delta D_s$ is replaced by

$$\left|\frac{\log\Delta C}{\log\Delta D_s}\right| \approx \frac{\sigma(\log C)}{\sigma(\log D_s)} \tag{3}$$

where $\sigma(\log C)$ and $\sigma(\log D_s)$ represent the standard deviations of $\log C$ and $\log D_s$, respectively. This approach of substituting the standard deviation of a variable for a single change (?) in that variable is equivalent to the reduced major axis technique for fitting a line to a scatter plot of x-y data (p. 200-204 in Davis, 1986). Eq (3) predicts the absolute value of $\log\Delta C/\log\Delta D_s$, but not the sign of this quantity. In some cases, the sign can be determined by inspection; in other cases it may be necessary to determine whether the positive or negative sign gives a better fit to the data (Davis, 1986).

<u>**Tracking grain size of bed sediment that is accessible to the flow**</u> Once it has been established that grain-size regulation of sediment transport is important in a particular sediment–transport system ($|\alpha|$ approaches or exceeds 1), it may be desirable to monitor changes in grain size of sediment on the bed. This is useful for at least three goals: (1) quantifying changes through time in the degree of winnowing or armoring downstream from a dam, (2) measuring the extent to which tributaries have contributed fine sediment to the bed of a channel (as is important in determining the timing of artificial floods in the Colorado River in Grand Canyon), and (3) measuring the spatial (depth-related) variation of grain size of sediment on the bed in pools, bars, and floodplains.

A dimensionless measure of grain size of sediment on the bed, $\beta$, can be defined as

$$\beta = \frac{D_b}{D_{bm}} \tag{4}$$

where $D_b$ is the median grain diameter of bed sediment at an instant in time, and $D_{bm}$ is the average of a sequence of median diameters at the same location. Thus, $\beta$ is a measure of the relative coarseness of sediment at one point on the bed. As Rubin and Topping (in press) showed, $\beta$ can also be expressed as a function of the dependent variable s $C$ and $D_s$ relative to their mean or median values

$$\beta = \left(\frac{C}{C_m}\right)^{\frac{-L}{JM-KL}} \left(\frac{D_S}{D_{Sm}}\right)^{\frac{J}{JM-KL}} \tag{5}$$

The exponent of the concentration ratio is negative, whereas the exponent of the grain-size ratio is positive (Table 1). As a result, the relative bed coarseness, $\beta$, increases as concentration decreases and as grain size increases (as intuition would suggest). Bed-sediment grain size is proportional to $\beta$ and can be calculated by multiplying $\beta$ by the time-averaged bed-sediment grain size for a particular reach.

The relation between bed sediment and suspended sediment expressed in eq (5) reflects at least three kinds of changes. First, grain size of sediment at a point on the bed (or within a reach) can change through time as a result of deposition of sediment from upstream or tributaries, winnowing of the bed, or erosion and excavation of underlying substrate. Second, the depth to which sediment in the substrate interacts with the flow may vary with flow strength (Wiberg, et al., 1994). For example, a weak flow that generates ripples on the bed will exchange sediment with the uppermost few centimeters of the sediment substrate. In contrast, a stronger flow that generates large dunes will exchange sediment with a greater depth within the substrate. Third, as stage increases, a river may gain access to finer sediment that occurs on high-elevation channel-margin bars and floodplains. Of these three changes, only the first reflects actual changes on the bed; the latter two changes in grain size reflect lateral or vertical changes in the region of the channel interacting with the flow. Measured changes in $\beta$ reflect all of these factors.

## EXAMPLES

**Calculation of $\alpha$** An example of grain-size regulation of sediment transport occurred during an experimental flood on the Colorado River in Grand Canyon in 1996 (Rubin et al., 1998; Topping et al., 1999). For the seven days of the flood experiment, clear water was released from Glen Canyon Dam at the rate of 1270 $m^3/s$. In response to this erosive flow, the bed at the Grand Canyon gage coarsened, which caused suspended sediment to both coarsen and decrease in concentration. The resulting negative correlation between suspended-sediment concentration and grain size (Fig. 2a) demonstrates that grain-size regulation was important during this event. Calculated values of $\alpha$ for data collected at 3 reaches during the flood were -1.5, -3.3, and -6.3, indicating that changes in sediment transport were regulated primarily by changes in bed-sediment grain size ($|\alpha| > 1$).

**Calculation of $\beta$** The same observations of suspended-sediment concentration used to calculate $\alpha$ can be used to calculate changes in the relative coarseness of sediment on the bed during the flood (Fig. 2b). Comparison with sampled bed sediment not only shows good agreement, but the smoother trend of the calculated values suggests that the calculations may be more representative of the system than measurements at a single cross-section. In this case, where river discharge was constant, changes in $\beta$ reflect actual changes in grain size of sediment on the bed. In other situations, where discharge is free to vary, calculated changes in $\beta$ can reflect changes in grain size on the bed, as well as changes in the region of the bed that is accessible to the flow. The predicted values of bed-sediment diameter are in close agreement with observed values. The predicted values have less scatter than the values observed at a single cross-section and may be more representative of the river.

## APPLICATIONS

The technique developed by Rubin and Topping (in press) and summarized in this paper has important applications with respect to: (1) designing sediment-transport measurement programs, (2) constructing sediment-transport models, (3) providing a starting point for the accurate determination of TMDLs for sediment, and (4) determining whether changes in upstream sediment budgets are positive or negative. First, this technique allows one to best design a sediment-transport measurement program. If, in a given situation, the dominant regulator of sediment transport is the flow, then an approximately stable relationship exists between the discharge of water and sediment transport (i.e., a stable sediment rating curve exists). In this case, measurements can be collected so that they best define a sediment rating curve (i.e., they are uniformly distributed across the entire range of flows). In contrast, if the dominant regulator of sediment transport is the grain size of the bed sediment, then sediment transport is controlled by changes in the upstream sediment supply and no stable sediment rating curve exists; measurements need to be closely spaced in time. In a similar manner, this technique provides a guide to knowing the pertinent physical processes to include in a sediment transport model. If the dominant regulator of sediment transport is the flow, then a model can be constructed that predicts a stable sediment rating curve by assuming that the channel geometry and bed sediment are in equilibrium with the flow. However, if the dominant regulator of sediment transport is the grain size of the bed sediment, then a totally different type of model needs to be constructed, one that routes sediment downstream from its source. A third application of this technique involves the calculation of TMDLs for sediment. In the case where the flow is the dominant regulator of sediment transport, TMDLs can be easily calculated using stable sediment rating curves (either measured or modeled). However, in the case where bed sediment grain size is the dominant regulator of sediment transport, TMDLs can only be calculated by determining the maximum naturally occurring daily supply of sediment. Finally, this technique allows upstream sediment budgets to be interpreted based on data from only one site. By determining whether $\beta$ is increasing or decreasing over long time scales, one can determine whether the upstream supply of fine sediment is decreasing or increasing over long time scales.

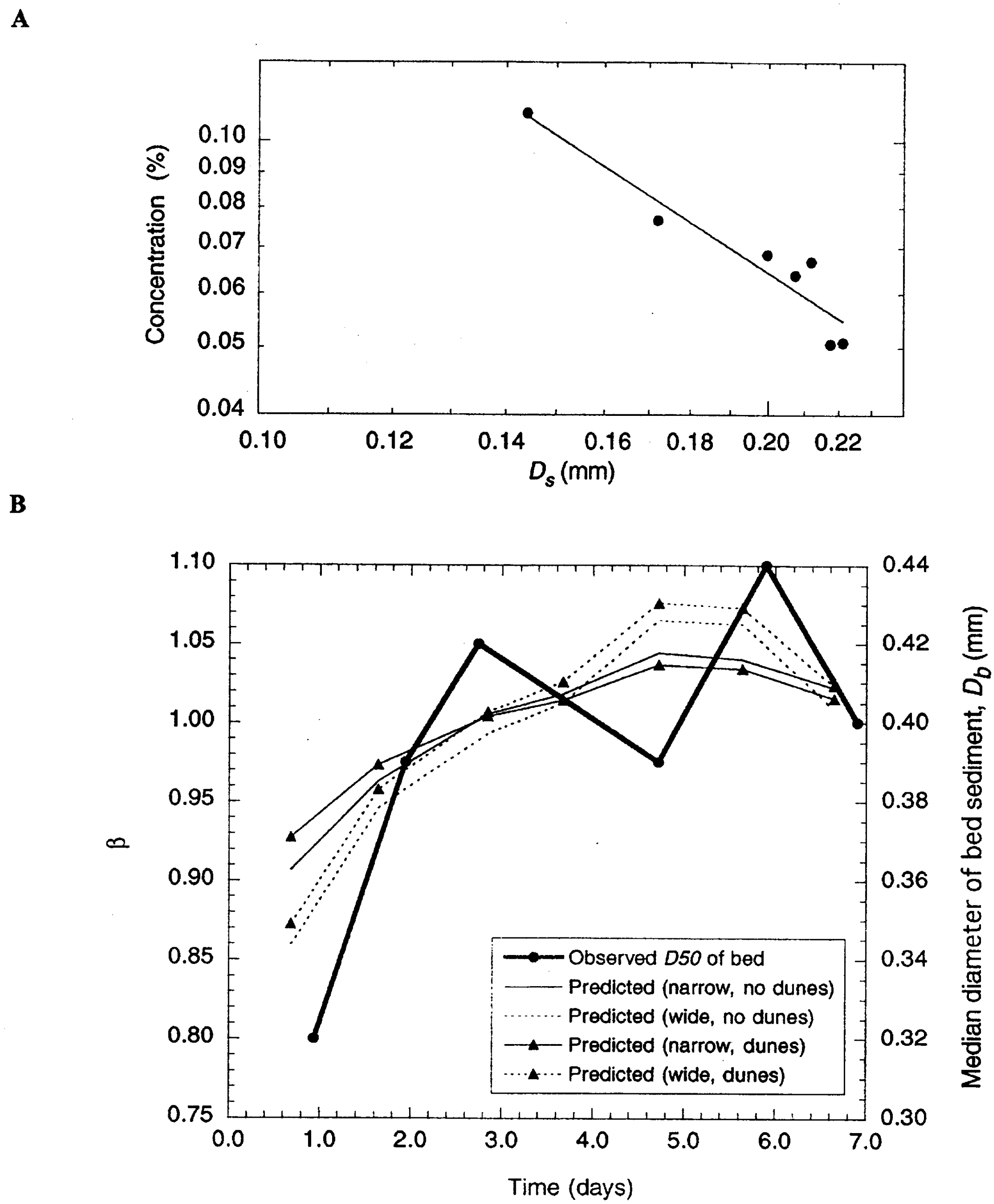


**Figure 2.** α and β during the 1996 flood experiment in Grand Canyon. **A.** Concentration and grain size for grain-size-regulated transport at Grand Canyon gage during the 1996 flood experiment. As sediment on the bed was winnowed, suspended sediment decreased in concentration and increased in grain size; concentration and grain size are negatively correlated ($\alpha$ = -1.5). **B.** Plot of β and predicted and observed bed-sediment median diameter. Observed bed-sediment median diameter was determined from samples collected at 3-5 locations at the Grand Canyon gage cableway (Rubin et al., 1998; Topping et al., 1999); β was calculated using eq (5) and suspended-sediment measurements; predicted values of bed-sediment median diameter were calculated by expressing β relative to the median diameter of all bed samples.

## REFERENCES

Davis, J. C., 1986, *Statistics and Data Analysis in Geology,* New York, John Wiley & Sons, Inc., 646 p.

Einstein, H. A., and Chien, N., 1953, Transport of sediment mixtures with large ranges of grain size. Missouri River Division U.S. Army Corps of Engineers, No. 2, 72 p.

Guy, H. P., Simons, D. B., and Richardson, E. V., 1966, Summary of alluvial channel data from flume experiments, 1956-61. USGS Professional Paper 462-I, 96 p.

McLean, S. R., 1992, On the calculation of suspended load for noncohesive sediments. Journal of Geophysical Research 97, 5759-5770.

Rubin, D. M., Nelson, J. M., and Topping, D. J., 1998, Relation of inversely graded deposits to suspended-sediment grain-size evolution during the 1996 flood experiment in Grand Canyon. Geology 26, 99-102.

Rubin, D. M. and Topping, D. J., Quantifying the relative importance of flow regulation and grain-size regulation of suspended-sediment transport ($\alpha$) and tracking changes in grains size of fine sediment on the bed ($\beta$). In press, Water Resources Research.

Topping, D. J., Rubin, D. M., Nelson, J. M., Kinzel, P. J., III, and Bennett, J. P., 1999, Linkage between grain-size evolution and sediment depletion during Colorado River floods. *in* Webb, R. H., Schmidt, J. C., Marzolf, G. R., and Valdez, R. A., eds., *The 1996 Controlled Flood in Grand Canyon,* Washington, D.C., American Geophysical Union, Geophysical Monograph 110, 71-98.

Wiberg, P. L., Drake, D. E., and Cacchione, D. A., 1994, Sediment resuspension and bed armoring during high bottom stress events on the northern California inner continental shelf: measurements and predictions, Continental Shelf Research 14, 10/11, 1191-1219.

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